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Citation for published version:

Harrison, G & Wallace, R 2004, 'Network integration of CHP: how to maximize access', *Cogeneration and On-Site Power Production*, vol. 5, no. 4, pp. 69-76.

Link:

[Link to publication record in Edinburgh Research Explorer](#)

Document Version:

Peer reviewed version

Published In:

Cogeneration and On-Site Power Production

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Network Integration of CHP *or* It's the Network, Stupid!

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The environmental benefits of Combined Heat and Power are significant and are a necessity for reducing the carbon burden of modern society. The European Union CHP Directive requires EU member states to have at least 18% CHP by 2012 and the UK target is 10 GW by 2010. Current UK installation is some 4.7 GW although a recent study projects that this may be missed by some 20%.

In common with other environmentally beneficial energy sources, such as renewables, CHP is mainly connected to medium or low voltage electrical distribution networks as distributed generation (DG). A significant justification for investing in CHP is the reduction in electricity imports from the network which attract a benefit equal to the purchase price of the electricity. Once site demand is satisfied then there may be potential to export and gain further benefit through electricity sales albeit at a lower rate. Clearly, such financial benefits must be set off against the cost of implementing and maintaining the CHP installation.

Connection of all grid connected plant fundamentally alters the operation of networks. There will be observable impacts on network power flows and voltage regulation particularly where generator capacity is comparable to local demand and specifically where export occurs. There is a risk that new connections will impact, adversely, on the security and quality of local electricity supplies and accordingly they must be evaluated carefully by Distribution Network Operators (DNOs). Where there are negative impacts, a range of options exist to mitigate them, however, under current commercial arrangements the CHP developer will largely bear the costs of implementation. The cost implications can make potential schemes less attractive and have played a part in restricting CHP deployment. As adverse impacts tend to be greater when plant exports to the network this explains to some extent the common requirement for anti-export equipment for CHP.

This article reviews the electrical impacts of connecting CHP to distribution networks and examines existing means of mitigating adverse impacts. Further, a new technique is briefly outlined that may assist the network integration of a greater capacity of CHP by allowing DNOs to better guide the siting and sizing of generation to minimise the sterilisation of network access as well as costly upgrades.

Traditional Distribution Networks

Historically, distribution networks were designed to convey power uni-directionally from the high voltage National Grid to consumers at lower voltages (Figure 1). Operated passively with limited control activity, the voltage control is provided by on-load auto-tap transformers down to the 11 kV primary substations which must then accommodate all voltage drops in the network below. While most urban networks are set up as ring circuits (called meshed systems) they are normally operated like rural, radial systems in order to keep fault levels low and simplify protection schemes.

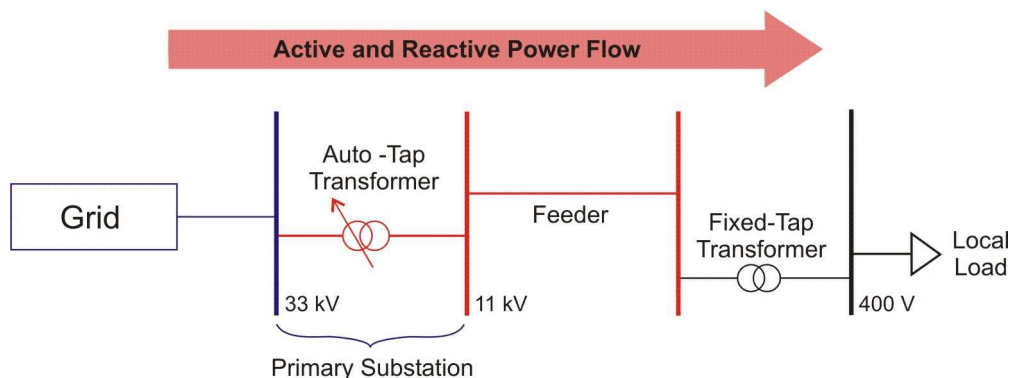


Figure 1: Traditional distribution network

Within the distribution network, the load carried tends to fall with distance from the substation with conductor size and rating reducing in response. This, together with the fact that conductors at lower voltages have relatively higher impedance means that low voltage networks possess significant impedance with consequent implications for voltage control.

It is a licence requirement for DNOs that they ensure that electricity received by consumers is within a defined statutory range in voltage and frequency. For example, the UK Electricity Safety, Quality and Continuity Regulations specify steady-state voltages within $\pm 6\%$ of nominal for systems up to 132 kV and within $+10/-6\%$ at 400 V. To achieve this, planning procedures specify more conservative limits, while assuming modest load growth from customers who possess a load profile that varies over time in a well defined manner. Until recently, distributed generation was rarely a consideration.

CHP Impacts on the Distribution Network

The connection of all forms of DG, including CHP, have network impacts given the alteration of network power flows (Figure 2). Generation within the distribution network lowers the load seen by the DNO and, particularly where the operation of generation is determined by heating demand or weather patterns, the load profile changes. Its presence can impact significantly through:

1. Bi-directional power flow and the potential to exceed equipment thermal ratings
2. Reduced voltage regulation and violation of statutory limits on supply quality
3. Increased short circuit contribution and fault levels
4. Altered transient stability
5. Degraded protection operation and coordination

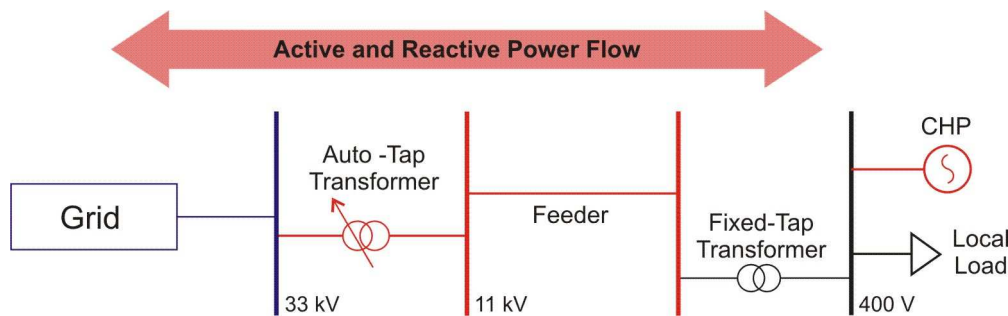


Figure 2: Distribution network with distributed CHP

Power Flows

Figure 3 shows four scenarios (i)-(iv) for embedding CHP within a simple, but representative, radial network supplying a local load via a substation transformer (1 MVA). The peak value of the local load is 400 kW at 0.98 power factor. A series of CHP capacities ranging from zero to 900 kW (at 0.9 lagging power factor) are connected to the remote end of the feeder.

- (i) With zero production the local load is supplied entirely from the network with all equipment operating within thermal limits and the losses in the feeder at 19 kW.
- (ii) With production at 300 kW, the power import from the network reduces, along with the losses. This may benefit the DNO by allowing deferral of network upgrades necessitated by load growth.
- (iii) With production at 600 kW and exceeding local demand, power will be exported back up the feeder and losses increase again, although the feeder and transformer loadings are within ratings.
- (iv) With production at 900 kW the export to the network raises losses beyond their original values, although it would take an even larger generator and low demand to exceed the transformer rating.

Thermal limitations brought about by increasing DG capacity are usually encountered first in substation transformers and switchgear, or at the edges of heavily tapered radial networks where plant capacity is several multiples of the local demand.

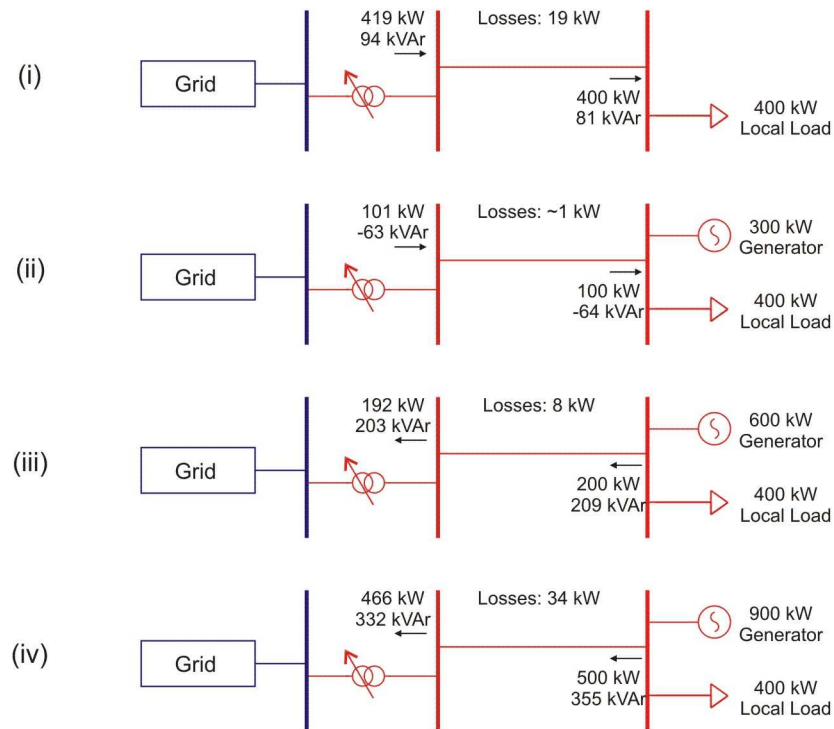


Figure 3: Feeder power flows with generator capacity

Voltage Regulation

Power flows along a distribution feeder will create a voltage gradient in the direction of power flow. Critically, where power flow reverses (as would be the case with CHP export) there will be a local voltage rise at the generator and load. Once again, cases (i)-(iv) are used to demonstrate the impact on the voltage profile (Figure 4). Clearly, when local demand is high and supplied by CHP the voltage rise is reduced, but where local demand is low, say overnight, more power is exported and the voltage rise increases. This effect could cause over-voltage protection to disconnect the plant and, consequently, voltage rise places a major limit on DG capacity, particularly in more rural locations.

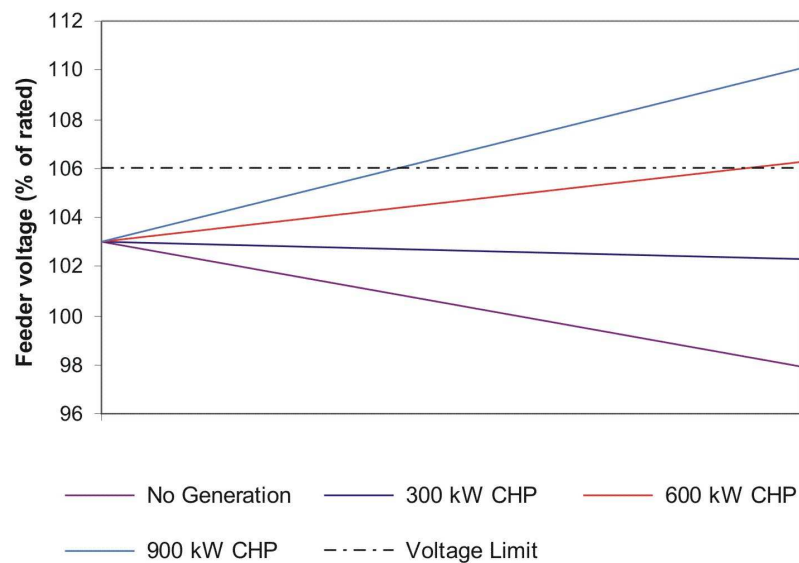


Figure 4: Feeder voltage profile with generator capacity

Fault Levels

In the event of a short circuit fault on the network all generators will contribute to the fault currents flowing. As such, the switchgear in the DNO network and that of the DG must be rated to withstand the effects of the combined fault currents. As the point of connection becomes more remote from the transmission network the intervening impedance increases lowering the network fault contribution falls. However, connection of DG will tend to raise them, at least locally. If fault levels increase beyond the rating of existing DNO switchgear, the switchgear must be replaced. This effect is most likely to affect urban or meshed networks.

Transient Stability

The ability of DG to remain connected to the network during transient conditions caused by load changes or network reconfiguration depends on network topography, the nature of the perturbation and the DG characteristics. During the transient conditions network stability is reduced. Some DG and, in particular the synchronous generators commonly used with CHP, can assist in restoring stable conditions. Hence, it is mutually beneficial for the DNO and developer that such plant should remain connected.

Protection

The distribution network is made safe and reliable by the provision and co-ordination of protection devices at energy sources, switching points or loads. The protection schemes were generally designed largely for uni-directional flow and their use with the bi-directional power flows from DG may lead to unstable or spurious operation. It is possible to adjust settings to ensure effective protection during DG operation but it must also be effective when it is offline; the trade-off can lower network protection levels.

Mitigating Impacts

The impacts arising from individual CHP schemes are assessed in detail following a connection application. DNOs appraise requests for connection under near-worst case operating conditions to ensure that customer quality of supply will not be impacted under normal operation. For instance, network power flow studies are carried out assuming that the DG is at maximum output, but that local load is at a minimum (typically 25% of peak). These conditions are chosen as they represent the largest reverse power flows and consequently the greatest local voltage change.

If the UK is to meet its targets for carbon-reduction, every technically and economically feasible CHP site that can be network-connected should be considered for development. Where the presence of such plant will adversely affect network operation, its impact must be mitigated in a way that encourages development, i.e., not unnecessarily punitive to the developer or DNO. There are a number of options open to the CHP developer and DNO to reduce adverse network effects arising from projects; the solution depends on the problem at hand.

Thermal Violation

Where there is potential to exceed the thermal rating of equipment then there is generally little option but to replace affected equipment with new plant of higher rating.

Excessive Fault Levels

One response to excessive fault levels is similar to that for thermal limitations where higher rated switchgear is fitted. Another approach has been to lower fault levels by raising network impedance, e.g., by opening parallel connections or the addition of series reactors; the downside is that voltage variations increase and it requires significant impedance to lower fault contribution. More recently, current limiters are being developed that operate very rapidly to prevent generators contributing to the peak fault current. These include the “Is-limiter” which is a form of smart fuse that employs a small charge to physically break the conduction path and protect networks from large close-up faults whilst allowing traditional switchgear to handle more distant ones. This device is commercially available but has found limited application in UK distribution systems to date. The holy grail of current limiter

research is the development of solid-state current limiters which avoid mechanical switching. There are two approaches: power electronic switches accompanied by means of dissipating the large energies involved or devices that use materials which possess significantly greater impedance at high currents.

Voltage Violation

Mitigating voltage violation offers most scope for innovative solution. Standard approaches include:

1. Constraining generator real power export
2. Reducing primary substation voltage
3. Importing reactive power
4. Conductor upgrading
5. Connection at higher voltage

Measures 1 to 3 can be effective in mitigating voltage rise but they are of an operational nature and have implications for developer revenue or local quality of supply. The remaining measures aim to limit voltage rise by reducing network impedance through greater conductor cross-sectional area or operation at higher voltage. While these tend to create fewer operational restrictions, the capital costs may be considerable. Figure 5 demonstrates the impact of measures 1 to 4 on voltage profiles for the network in Figure 3 with minimum (25%) local load as required by a 600 kW generator that would otherwise raise voltages above the +6% limit.

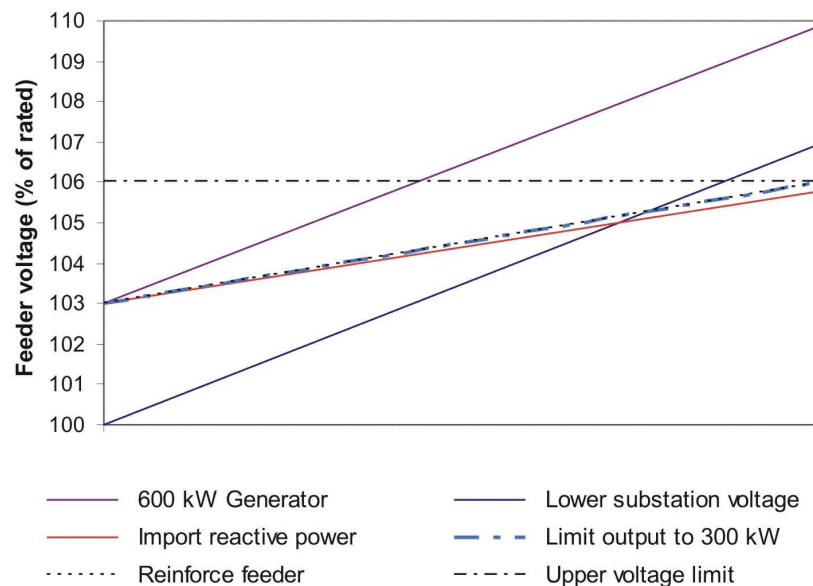


Figure 5: Feeder voltage profile with mitigation measures

Financial and Management Implications

Mitigation strategies will generally incur costs, either operating costs borne directly by the developer or capital costs borne by the developer and/or the DNO. Current ‘deep charging’ arrangements mean that the DNO can, as a condition of connection, insist that the developer finances necessary expenditure. This may add significantly to the capital cost of the project and, particularly for smaller projects, may render them non-viable or at the very least preclude export to the network. An alternative ‘shallow charging’ system will eventually be implemented wherein the DNO finances the necessary network upgrading and collects Distribution Use of System (DUoS) charges from generators. In doing so, the DNO will need to justify the costs in terms of the benefits created.

A further risk can emerge from the current first-come-first-served policy wherein network access is guaranteed once a connection agreement is signed. This means that subsequent developments must not impact adversely on prior connections and can lead to an early and maybe minor connection preventing development of other larger sites, effectively ‘sterilising’ areas of the network. The current system can

also lead to “free-riding” which occurs when design or equipment standards require an upgrade that exceeds the minimum required by the developer that financed it; subsequent applications may be able to access and this additional capacity at a much lower connection charge. Both issues complicate and restrict DG development and commend the need for planned holistic development.

Maximising Access to Distribution Networks

It appears that if developers or DNOs are prepared to finance network reinforcement in a piece-wise fashion, then many of the restrictions to individual schemes are reduced or avoided. However, this is unlikely to lead to full development of the CHP or renewable resource in a network area and there needs to be a better strategy to develop the network in a way that provides greatest access for a given level of network investment.

Recent studies of the transmission network in Scotland have identified areas where new generation (primarily renewable) could be absorbed by the existing and upgraded transmission network. As much of the new development will be within the distribution network, similar studies will be required lower down in the network.

It is possible to appraise available network capacity on a location by location basis but in even a small section of the distribution network there may be several hundred connection points. This and the greater influence of voltage necessitates automation of repetitive and time consuming manual studies. Even then, such results may be optimistic because they ignore the interdependence of the network. The number of applications for connection of renewable or CHP-based DG in the UK means that development is a parallel activity. There are often multiple applications for access to similar points within an area of the network. In these circumstances, determining available network capacity is a complex problem that is not amenable to repetitive simulation. In response, a range of powerful techniques (based on Optimal Power Flow) have been developed by the authors to determine the maximum simultaneous access for plant across some or all network locations. This takes full account of adjacent development and network constraints. Their most powerful application is with scenario studies within a selected area of the distribution network, where network access and DG development can be modelled sequentially in time and with concurrent developments. This allows not only connectable capacity to be ascertained but provides a basis on which DNOs can guide development within their network and working with CHP, and other, developers, maximise access, clarify the need for network upgrades and avoid network sterilisation.

Conclusions

Connecting CHP and other distributed generation to the distribution network creates a range of impacts that must be limited to protect the security and quality of electricity supply. Mitigation techniques currently employed may add significantly to the cost of developments and deter investment in CHP. The inappropriate siting of new generation, or poorly phased development can lead to the sterilisation of an entire area of network and lowers the opportunity for developing surrounding CHP and renewable potential without network upgrades. Government targets for CHP and other distributed generation will require more holistic development of the available potential and network infrastructure.

Authors & Acknowledgements

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They acknowledge with gratitude support provided by EPSRC (research grant number GR/N04744).

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